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Master's Thesis

Programmable Matter Research
based on 4D printing

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Department of Materials Science and Engineering

Graduate School of UNIST

2017

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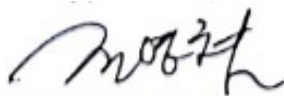
Programmable Matter Research based on 4D printing

A thesis
submitted to the Graduate School of UNIST
in partial fulfillment of the
requirements for the degree of
Master of Science

Sung Chan Lim

06. 17. 2017

Approved by



Advisor

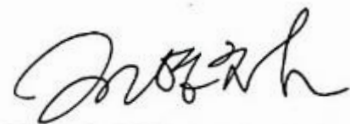
Young Chul Jun

Programmable Matter Research based on 4D printing

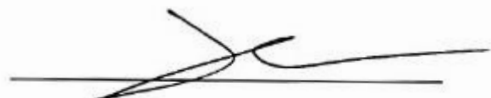
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Abstract

As a concept suggested by Skylar Tibbits of MIT in 2013, 4D printing is a field with many new possibilities. 4D printing produces programmable matter that responds to exterior stimuli and changes its structure or properties into the shape designed in advance, through 3D printing. ^[1] One of the advantages of 4D printing is that a motion can be realized in a simple constitution in order for a certain material to move even without a complicated driving mechanism like a motor. ^[1] This paper first explains 3D printing and 4D printing and then deals with 4D printing using the properties of Poly-Lactic Acid (PLA), which is a shape memory polymer, and 4D printing using a bistable structure. In the case of 4D printing using PLA, we applied the properties that the shape is restored to the original form at a state higher than glass temperature to 3D printing and tested what structure of 4D printing would be possible in the future. In the case of the bistable structure, we made the basic elements of a mechanical bistable structure in order for 4D printing using Shape Memory Polymer (SMP) to produce more efficiently, and prepared the ground that can realize the diversified and complicated mechanical movements.

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Introduction

The field of 3D printing is recently drawing attention in industry together with the emergence of the 4th industry revolution. ^[2-6] 3D printing is better than traditional manufacturing methods in several points. Its main advantage is that it does not cost additionally in making a new form. And by carrying only digital objects, we can easily reproduce them in other places. ^[2] The reason why these parts come to be an attractive merit is that, different from the existing method of production, 3D printing piles up the layers one by one and makes the production in accumulation no matter what form it has – i.e. additive manufacturing. ^{[2][3]} With such a merit, 3D printing has drawn attention and opened new possibilities, but it still has limitations. 4D printing is gradually attracting attention as something that can solve these limitations and produce more useful objects. ^{[1][8-9]} 4D printing is a concept that was introduced for the first time in 2013 by Skylar Tibbits. ^{[1][9]} In fact, the concept of 4D printing can be simply explained as producing programmable matter through 3D printing.

The biggest difference of the matters produced through 3D printing and 4D printing is that in the latter the shape or property can change after printing – the additional 4th dimension here is ‘time’. In other words, the form and properties of the goods produced by 3D printing are fixed and static, but those produced by 4D printing have dynamic properties even after being produced. ^{[1][8-9]}

For these properties, it is called 4D printing because the post-production transformation is added to 3D which are the matters that have been produced in the meantime. Since the physical properties of the product manufactured by 4D printing can be changed even after printing, it has more advantages than 3D printing. We can indicate self-assembly as a typical example. If making the material possible to self-transform and self-assemble after it has been printed, we can produce a bigger structure that is difficult to make by a 3D printer. ^[8-10]

In addition, different from the existing 3D printing that has additional costs in assembling after making each part, we can even use what has been produced right away without an additional process of assembly since it self-assembles. Taking a look at the fields that this 4D printing can be applied in the future, we can use it in various fields such as health care, infrastructure, automobile, aerospace, military, manufacturing, packaging, consumer durables etc. On that account, we can expect that it will make a huge impact on various fields with the development of 4D printing in the future. ^[9]

We can briefly explain here about the power of influence of 4D printing on each field as follows.

In case of **health care**, there exists an applicable possibility of 4D printing to tissue engineering.

Tissue engineering restores, maintains, and improves the function of biological tissue and overall organs. By producing and printing self-assembling human scale biomaterials, we can easily produce them customized to the wide variety of people. An easy custom solution like this means we can produce them far much cheaper and easily than the current method. ^[9]

In the case of **infrastructure**, there must come a point as time goes on that various kinds of infrastructure such as the pipes of water supply and sewerage are needed to invest for replacement due to increased demand or a changing environment. However, if producing them through 4D printing, we can produce self-adaptable pipes. Since they adapt themselves to the diversified situations such as environmental change, etc. if they are self-adaptable, we can drastically decrease the necessity of replacement of the pipes. Apart from these pipes, we can diminish the necessity of replacement of various infrastructure. ^[9]

In the fields of **automobile**, **aerospace** and **military**, we can also make things that can respond to diverse environments properly. For example, we can produce the automobile tire that can work well in various situations such as an icy road, rainy street, dry road, etc., or that can self-repair when damage occurs to the body of automobile or airplane. We can save the cost of assembly, transport expense and space expense in **manufacturing**, **packaging** and **consumer durables**. Because the self-assembly product can assemble itself to the finished goods in any place at any. What the products can be assembled in any place at any time means that we can remove the labor cost in need for assembly. Secondly, we can save much expense of transportation since we can assemble later after transporting them in an easy-to-carry shape. Lastly, if the shape can change any time, we can save the occupied space at home through making them possible to occupy little in normal times and to be used only when necessary. Like this, we can expect that 4D printing will impact much on various fields. ^[9]

This study has a character of pilot research prior to a full-scale study of 4D printing in the future. The contents dealt in this study is 4D printing using Shape Memory Polymer(SMP) that responds to heat and 4D printing using the bistable structure responding to mechanical force. This study is not enough to apply yet, but we performed a test in order to show the possibilities of what we can do with 4D printing in the future. In addition, we are dealing here with 4D printing by SMP and 4D printing using the mechanical bistable structure independently, but we think that we will be able to get a synergy effect by combination of the two kinds of properties in the future.

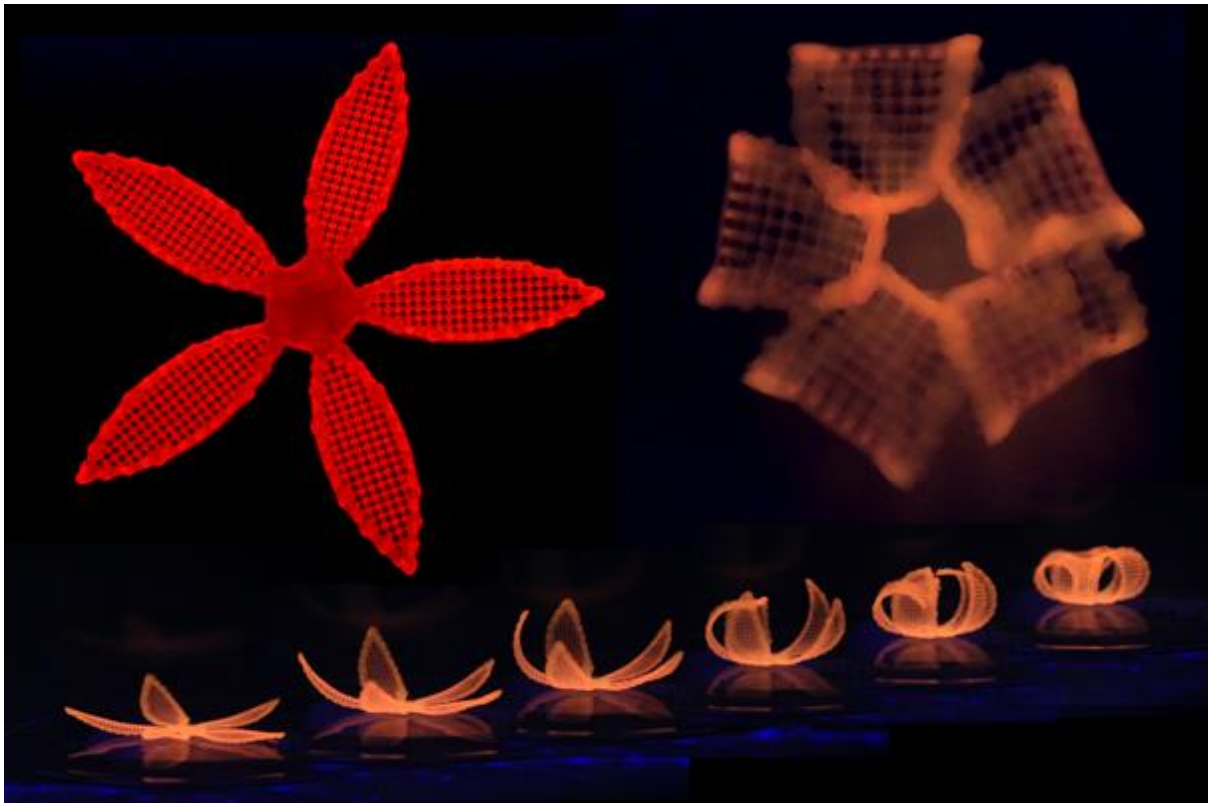


Figure 1.1

An example of a 4D printed flower^[11]

When immersed in water, the flower programmably change shape.

2. Background

Prior to explaining the contents of the study, we are going to explain in this section about the concepts of the contents dealt in the paper. We deal with 3D printing, 4D printing, and the programmable matter in the contents. And, we are going to show some kinds of examples additionally for what possibilities 4D printing has.

2-1. 3D printing

3D printing is a field that is very popular to the common people and draws attention through various media in recent years. Different from what we think, 3D printing is a field that has a long history of study begun since 1980's. Thanks to the studies on the field for a long time, many things have been commercialized recently. For an example of commercialization, famous companies such as Adidas etc. introduced 3D printing and began to use in industry, or various home 3D printers were sold and they began to use 3D printing at the typical family home. As mentioned earlier, 3D printing is a field that many technical steps have been progressed by studies for a long time. To evaluate the technical maturity of this 3D printing, it's right to say that 3D printing is already entering into the stage of completion in technology since 3D printing is in the stage that people already begin to apply it to industrialization and they expect that even the stage of commercialization will have completely progressed in around 2030. (Normally, technologies are classified into the stages of concept, realization, and commercialization, and evaluate the technical maturity in those criteria.) The definition of this 3D printing is that "3D printing fabricates objects by controlling the placement and adhesion of successive layers of a 'build material' in 3D space." Since 3D printing works by piling up the successive layers one by one, it is also called like 'additive layer manufacturing'(ALM) or 'additive manufacturing'(AM).^[2]

The key point here is that it produces the material to be made through piling up the successive layers one by one. We can more clearly understand the producing method of 3D printing when checking the process of 3D printing, and it's stipulated as follows.

1) 3D printing begins with making a digital object using a design application. Normally this is the stage that we draw directly the structure to be made through a program such as CAD or make the object to be made into a computer file through 3D scanner, etc.^[2]

2) **The digital object made by slicing software is divided into many cross-sectional layers.** Depending upon how it is sliced in tiny resolutions, the resolution of Z-axis is determined in this stage.
[2]

3) **The information divided at stage 2 is carried to 3D printer and produced.** It takes from several hours to several days in this stage. Time varies according to the complexity and size of the model and the resolution of Z-axis.
[2]

4) **Post process of the object produced by the printer comes last.** The rough surface is made smooth or the supports produced in the process of fabrication of the object is removed in this process.
[2]

As you can check it at the process again, no matter what form it has, we can produce it all by piling up the layers one by one only if we have a digital object. On this account, when we are to produce something new, there is an advantage that we can make a digital object of the shape to make without addition of equipment or process and produce various objects through the same 3D printing process. Lastly, to additionally explain about the method of 3D printing, it is common in 3D printing that we fabricate by piling up the layers one by one, but the method is divided into various ones depending upon the way to pile up. 3D printing has the methods such as Material Extrusion, Vat Photopolymerization, Material Jetting, Binder Jetting, Powder Bed Fusion, Directed Energy Deposition, Sheet Lamination.
[2]

The simple explanation on each method is as follows.

Material Extrusion is a method that pulls out semi-liquid materials from the nozzle in order to make successive object layers.
[2]

Vat Photopolymerization is a method that hardens the base or surface of the vat containing the liquid photopolymer by laser or other light source in order to produce successive object layers.
[2]

Material Jetting is a method that the print head drops the liquid build material like a normal inkjet printer and produces through hardening it with UV or heat.
[2]

Binder Jetting is a method that produces by hardening the powder with partial scattering of the binder in the process of piling up the powder layers one by one.
[2]

Powder Bed Fusion is a method that produces by partial hardening with laser or heat source when piling up the powder layer after layer.
[2]

Directed Energy Deposition is a method that directly hardens with UV or heat source when depositing the powder build material.
[2]

Sheet Lamination is a method that produces through piling up sliced paper, plastic or metal in one layer after another. ^[2]

We used Fused Deposition Modeling(FDM) method and Polyjet method in the study that we processed at this time. FDM belongs to Material Extrusion and Polyjet belongs to Material Jetting. FDM is a method that piles up one layer after another by melting the thermoplastics at the temperature higher than the melting temperature and pulling them out through the nozzle. It's the most common method that is used for household purposes. Polyjet is a method that jets the photopolymer and cures with UV. This method has a merit, in that we can produce a high resolution. ^[10]

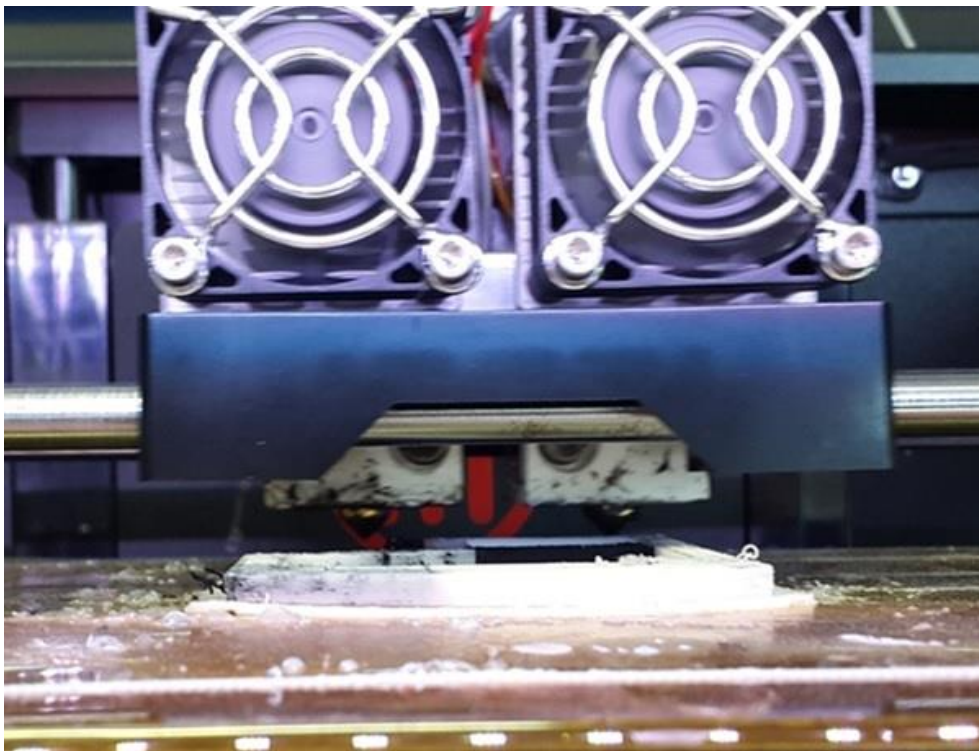


Figure 2-1.1

3D printer pictures (Dual head extruder 3D printer. Model: MAKERBOT REPLICATOR 2X.)

2-2. 4D printing

As a concept that was made for the first time in 2013, 4D printing is a very new field compared to 3D printing and has many features that can be improved.^{[1][8-9]} 4D printing is now passing through the stage of realization out of the stages of concept, realization, and commercialization which were told when explaining earlier about the technological stages of 3D printing. There is no clear definition yet about 4D printing. So, we can largely construe it as a process that prints the 3D objects with additional functions.

As told by Skylar Tibbits who performed an experiment to make programmable matter through 3D printer and first suggested the term 4D printing, we define it in this paper for now that “4D printing is a process making the programmable matter by 3D printer.” From this definition, we can say that 3D printing is to fabricate simply 3D objects, but 4D printing is to manufacture the produced object that can respond to external stimuli and operate as designed. (The programmable matter is explained below.) In other words, the biggest difference between 3D printing and 4D printing is that different from 3D printing that its shape or characters are completely fixed after the object has been fabricated, 4D printing can vary. Even for the name of 4D printing, they add the time axis to the three-dimensional space and call it 4D printing since time varies when the form or properties change.^{[1][7-11]}

The advantage of 4D printing is that since 4D printing manufactures the programmable matter by 3D printer, it has both of the two merits that the programmable matter and 3D printing have. In other words, one advantage is that we can easily produce and use complicated programmable matter since it fabricates the programmable matter by the merit that easily makes any complicated device of 3D printing. At the same time, it has a merit that we can make a product which can properly respond to external changes or stimuli after having been produced since the material fabricated with 3D printer is a programmable matter. Through these advantages, 4D printing can easily produce the 3D structures that have diverse functions such as self-assembly or self-transformation. In conclusion, we can say that 4D printing will have more possibilities than 3D printing. We are going to deal with the examples of prototype on the applicable possibilities in section 2-4.^[7-11]

Two kinds of elements are needed for 3D printing to be 4D printing. The first one in need is storage of the potential energy for the transformation of shape or properties. There are various methods such as magnets, elastic strands, nitinol wirers, etc. to get potential energy which is necessary to transform in 4D printing. We performed an experiment in this thesis with the force by the strain caused by the transformation of SMP and the force generated from elastic energy.^[1]

The next thing needed is programmability.^[1] Design and placement on what way it is to be changed are needed. We don't need to consider it in case of 3D printing since the properties of the fabricated goods do not change, but in case of 4D printing, we have to consider in advance what way it has to

change in order to obtain the expected results. For example, we have to consider to set a limit of the bending angle with a rigid material in order for the to-be-bent parts to be curved in a proper angle. In other words, we must design what results will come out when responding to external stimuli before producing in the beginning.^[1]

As 4D printing is in the initial stage of study, there are the following problems to be solved. In **design part**, at first, it has things to encompass dynamic components with a design application such as CAD when making a digital object for the matter to be manufactured. For **materials**, we have to find the materials with multifunctional properties which are necessary for us to print in 4D. For **adhesions**, there is a problem making them easily adhere to each other when printing many different matters. And lastly, 4D printing has to solve the problems in what way it is going to make, store, and use the **energy** which is necessary to respond to external stimuli.^[8] Despite these problems, researchers will solve the problems in the future and enable the transforming digital information in the virtual world to be realized in the real world.^[8] It can be estimated that it will give a very big impact.

To explain this part a little more precisely, we will come to be able to design much more diversely than the current 3D printing since it can easily realize many movements when designing the products. Since this means that the obstacles existing in producing certain goods disappear in the end, we can produce the goods with more diversified shapes and functions. In other expression, it implies that we can easily produce complicated goods in cheap price in the future. If possible to realize movements to the goods, it means that functions such as self-assembly can be easily realized. These abilities will unfold many possibilities. For example, when transporting goods, we can seriously decrease transportation cost through manufacturing them to fold well with each other and we can also make them change into finished goods later.^[9] We can fabricate the produced goods to be self-optimized to the user as well. In 3D printing, we must produce items one by one separately by changing the conditions when making the prototypes, etc. with various conditions, but in 4D printing, we can produce a prototype to meet various conditions and make diverse comparisons.^[8]

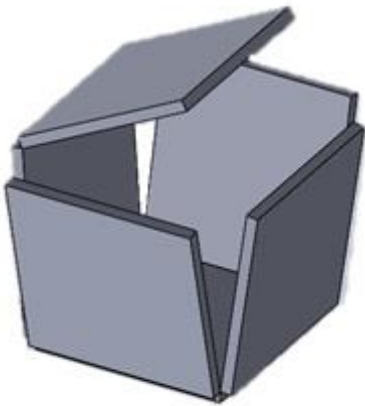
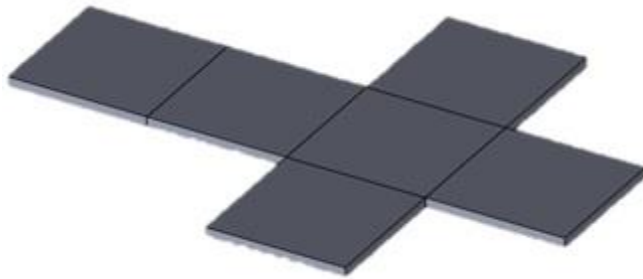


Figure 2-2.1

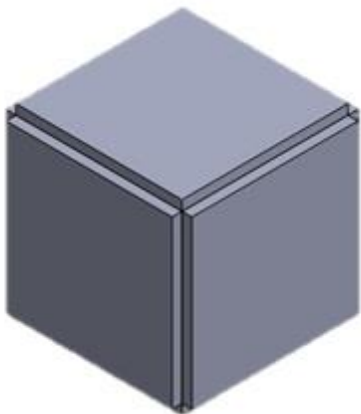
4D printing Example of Self-assembly or Self-transformation

The structure made with 4D printing can change its shape after printing.

Top: initial state (planar figure of cube)

Middle: sel-assembled

Bottom: final state (cube)



2-3. programmable matter

Programmable matter means matter with characteristics (shape, density, moduli, conductivity, optical properties, etc.) that change due to external stimuli according to what has been designed in advance by people. In other words, it's the matter that senses and responds by itself. For reference, the properties of programmable matter are made from the intrinsic characteristics of material itself. The similar examples with the programmable matter can be commonly found in our surroundings, and we can give it as a typical example that the plants blossom when a time suitable to blossom comes and they grow following the light. Programmable matter is the material that is made to respond properly and usefully as designed in advance when external stimuli come in using diverse methods such as smart materials, etc. ^[8]

The biggest merit of this programmable matter is that we can simplify the device. For example, let's think of making a device that takes in and responds to light. When making in a general method, it needs a sensor taking in the light, a circuit to grasp the information of the sensor, an actuator to operate from this, and the parts to supply electricity. In the case of an object made with programmable matter, however, it can realize the same functions with a very simple structure since the material itself senses the light without all of these parts. It's 4D printing as told earlier that produces this programmable matter with 3D printing. The advantage we can obtain through 4D printing is that we can easily fabricate the complicated programmable matter comparing to the existing method, and produce the programmable matter suitable to a certain situation whenever it needs. In other words, 4D printing, as stipulated earlier, has all merits of 3D printing and the programmable matter. ^[8]

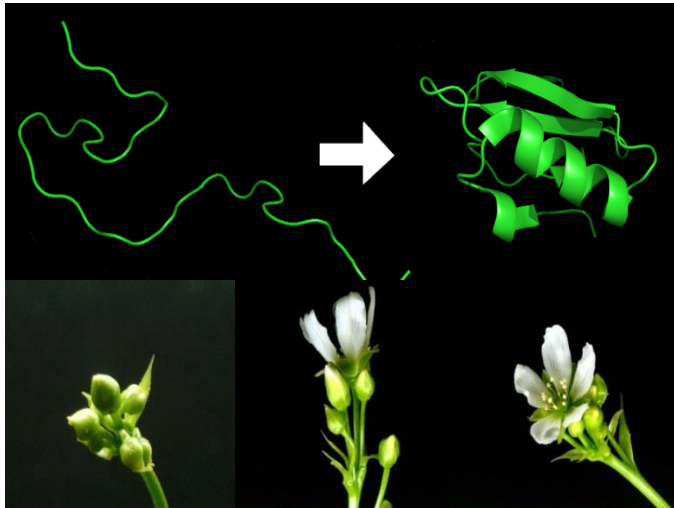


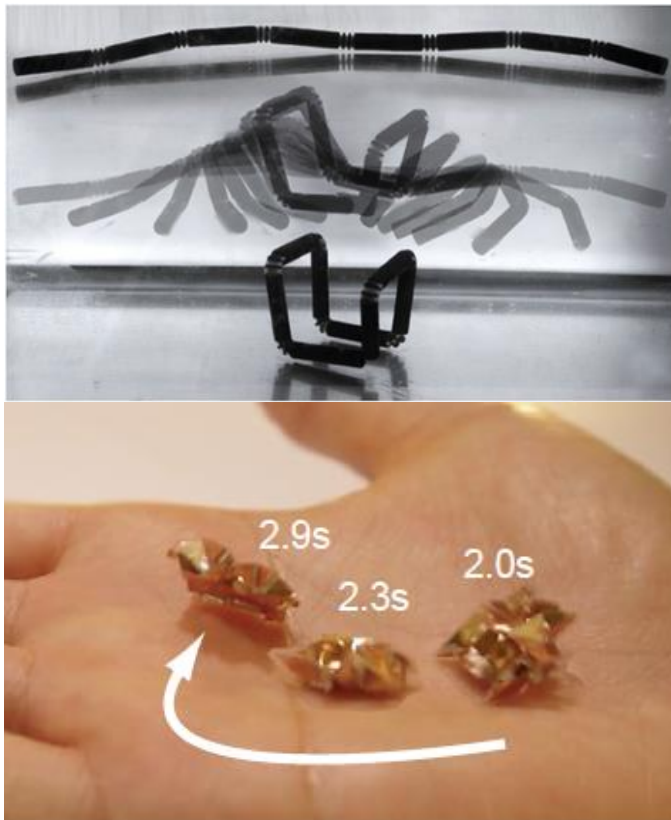
Figure 2-3.1

Example of programmable matter

Plants are similar to programmable matter^[12]

Programmable meta responds to external stimuli.^{[8][13]}

Nature



Programmable Matter (or Programmable materials)

2-4. Comparison between 3D printing and 4D printing

We have explained on 3D printing, 4D printing, and the programmable matter until now. Here we compared the difference between 3D printing and 4D printing. In case of 3D printing, we use the materials such as thermoplastic, metal, etc. that the properties are fixed. In case of 4D printing, on the contrary, we mainly use the materials like smart materials that the properties can change. Like this, the rest of differences keeps appearing from the difference of used materials, and in case of 3D printing, we can design without consideration that it will change since the properties of material do not change, but in case of 4D printing, we must design in consideration of change since the properties of material change. In other expression, 3D printing is fixed and static after having been produced, but 4D printing can do something active since it can change. Therefore, in case when printing and using with 3D printing, we only make a 3D structure that the shape is fixed like the prototypes or tools, but 4D printing can produce various things with functions in addition to the 3D structure. Lastly, we compared and summarized below about 3D printing and 4D printing. ^[6]

	3D Printing	vs.	4D Printing
Materials	<ul style="list-style-type: none"> • Thermoplastic, Photopolymer • Metal, Ceramics • Biomaterials, nanomaterials 		<ul style="list-style-type: none"> • Smart materials • Multi-materials
Design	<ul style="list-style-type: none"> • Fixed 3D structure (CAD) 		<ul style="list-style-type: none"> • Need to consider a structural change over time
Printing	<ul style="list-style-type: none"> • 3D Printer Ex) FDM, SLS, SLA etc. 		<ul style="list-style-type: none"> • 3D Printer with multi-materials • Smart 3D printer Ex) modified nozzle, binder, laser, etc
Change	<ul style="list-style-type: none"> • Fixed as-printed 		<ul style="list-style-type: none"> • Changed in shape, color, function, etc.
Application	<ul style="list-style-type: none"> • Prototype, tools, toys, fashion, automobile, aerospace, defense, and bio/medical device 		<ul style="list-style-type: none"> • Add active, reconfigurable features to all 3D printing applications

Table 1

Comparison between 4D printing and 3D printing ^{[6][8]}

2-5. Examples of 4D printing

In this part, we give an example of prototype created using 4D printing for self-assembly and self-adaptation that we told earlier in order to help understanding when explaining the advantages of 4D printing together with the example for the possible parts created using 4D printing.

Underground Pipes (Example of Self-adaptation)

Different from the general pipes which are used at the moment, those that are made by 4D printing can move like the picture (Figure 2-5.1) according to the surrounding environment. These movements of pipes can help and maintain the flow in the pipes very smoothly. ^{[9][14]}

Shoe (Example of Self-assembly)

We printed the shoe in this picture (Figure 2-5.2) with 3D printer in a two-dimensional structure, and it self-transformed and could be the shoe like the picture (Figure 2-5.2). Like this, if making and transporting the goods, we can save much cost of space when transporting. We can apply this not only to the shoes but also to various other goods. ^{[9][15]}

Military Boots (Example of 4D printing vision)

Largely, there are standard boots and jungle boots for combat shoes at the moment. The standard shape is the combat shoes that we commonly think and has an excellent effect of waterproof. However, it has a disadvantage that does not get dry easily when getting wet since it is not good at ventilation due to the effect of waterproof. The existing standard combat shoes brought about many problems at the Vietnam war that was waged in the jungle with so many wet lands, and thus the jungle boots were produced to make the combat shoes get dry fast which is to be got wet anyway. Different from standard boots, however, these boots have a demerit that is lack of waterproof capability. If making these boots with the programmable matter, they have an excellent waterproof effect before getting wet, and it can change to get dry very well due to the enhancement of ventilation capability in case of getting wet. In other expression, it can satisfy the two advantages of standard boots and jungle boots at the same time by self-adaptable programmable matter. And, if the boots can be produced by 3D printing, we can get the merit that only with the preparation of materials, we can solve the existing difficulties that we have to prepare respectively for the size of each soldier's foot. If there are something to be made in various shapes that the properties change themselves fit to these various environments, we can obtain a very big effect through 4D printing like this. (Clothes, tire, etc.) ^[16]



Figure 2-5.1
Underground Pipes of 4D printing examples. ^[14]
The pipes change shape to help move water.

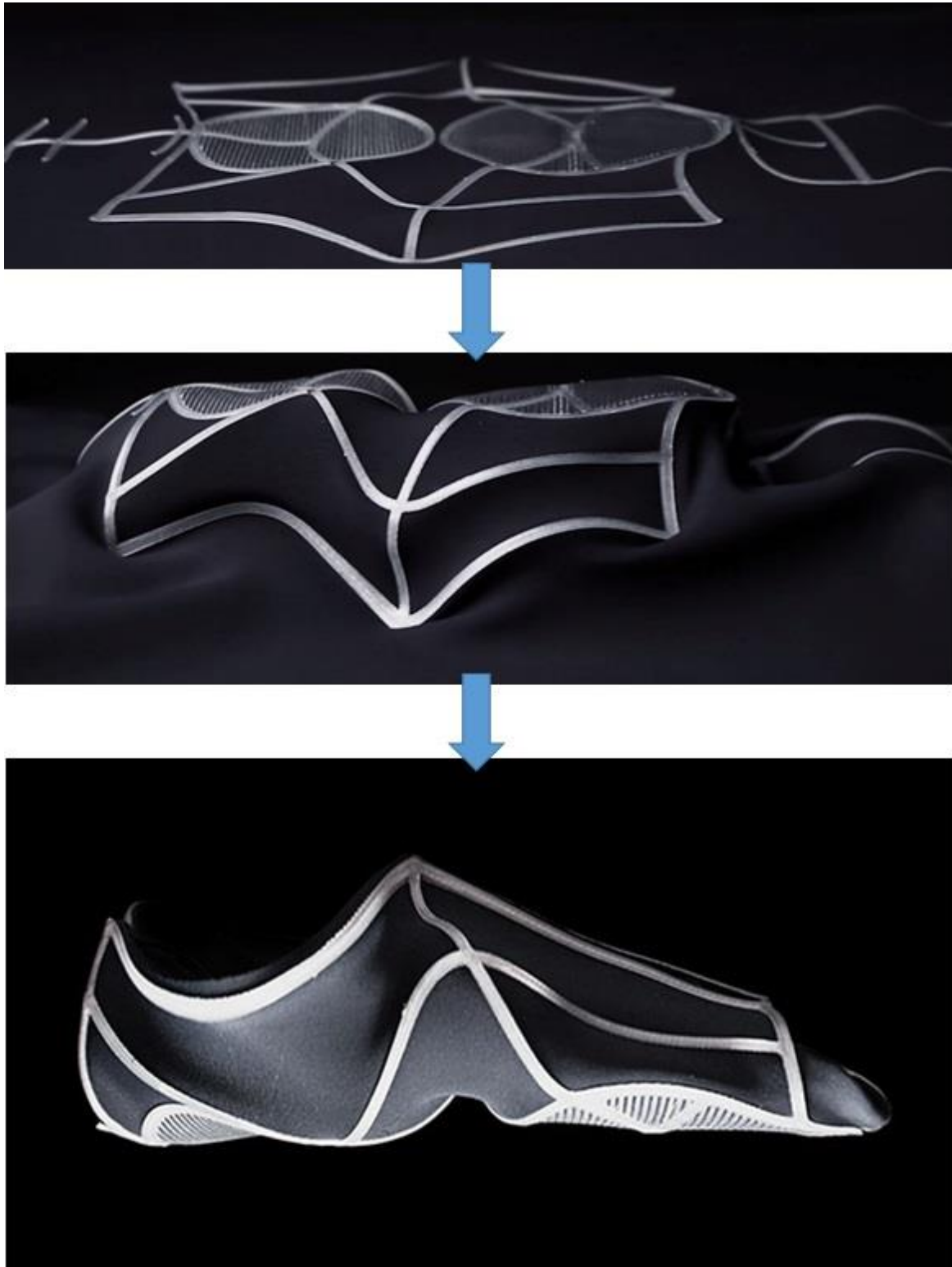


Figure 2-5.2

Self-assembled shoe of 4D printing examples.^[15]

Self-assembly of Programmable matter can be used to reduce shipping costs.



Figure 2-5.3

Left: standard boots^[17] Right: Jungle boots^[18]

Each boot has the opposite advantage. Standard boots have watertight and jungle boots have dry well.

3. 4D printing based on SMP

We fabricated the programmable matter in this study with a 3D printer by using the shape memory polymer and printed it in 4D. In this chapter, we gave a simple explanation on the shape memory polymer that has been used, on the process of 4D printing using SMP, and dealt with the results of experiment. We created a sample as the experimental result that can show what will be possible in the future with 4D printing using SMP. The method we applied to SMP in this process was Joule Heating and direct heating for the change of external thermal environment.

3-1. Shape memory polymer

SMP is a polymer that returns to the original shape the same as the shape memory alloy when the temperature goes up, and tries to return to the original shape in a temperature higher than glass temperature. To explain the principle how SMP restores the shape, if melting the shape memory polymer and producing a structure through raising the temperature higher than melting temperature, SMP is made into a state that the strain is not generated. If raising the temperature higher than the glass temperature in this state and giving a transformation of shape, the strain comes to be generated in SMP. If cooling below the glass temperature in this state generated with the strain, SMP comes to be hardened solidly and the energy by the strain comes to be stored as it is. So, if the temperature goes up higher than the glass temperature again in this state, it restores the original shape by the stored energy of the strain. SMP is called a smart material due to the property that the original shape is restored like this, and it is a very useful material when making the programmable matter. In addition to this, PLA is much used for the materials of 3D printer, and thus it is very useful material for 4D printing since it's good to make a test sample. ^[19]

PLA

PLA, i.e. Poly-Lactic Acid, is a material that is very commonly used in 3D printing, and it has many advantages such as being comparatively safe to the human body since it is extracted from corn. Above all, it has been used very usefully in this experiment since it has SMP properties. ^{[2][5]}

Conductive PLA

It is a material that is made for electricity flow by mixing graphite to PLA. However, it has a demerit that is more rigid than a simple PLA.

MM3520

As a material that reaches glass temperature at around 35 degrees Celsius, it can be used for 4D printing that responds to the body temperature. If containing moisture, however, it shows a disadvantage difficult to handle such as expansion, etc. since bubbles are generated after melting. ^[20]



Figure 3-1.1

SMP materials

Top: PLA

Middle: Conductive PLA

Bottom: MM3520

3-2. 4D printing process

We are going to explain on the process of 4D printing using SMP. 4D printing consists largely of stages of printing, programing and actuation.

Printing process

The printing process is the same stage as the existing 3D printing. It's the stage to make the material of thermoplastics into filament and to print the structure with a 3D printer. But if there is a difference, it's to print the 3D structure with SMP.

Programing process

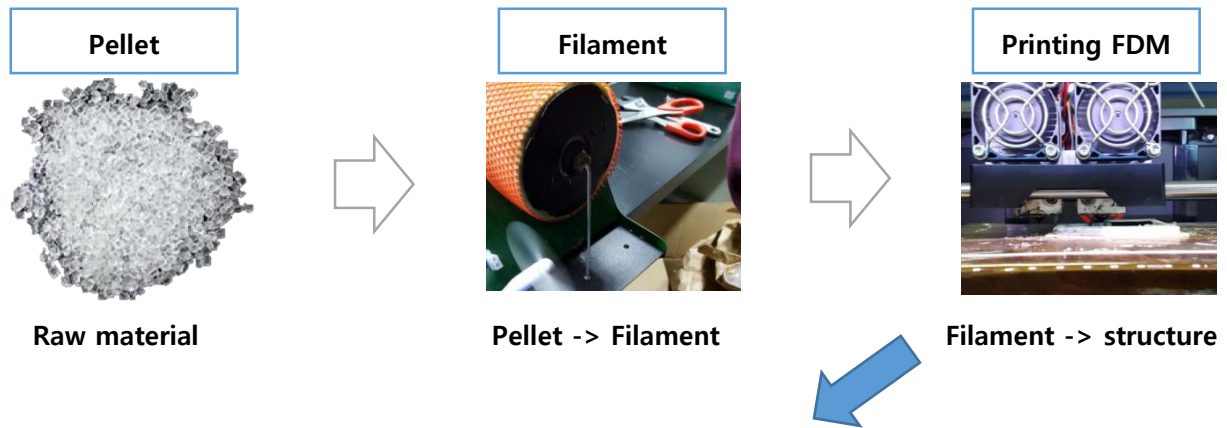
As a part to determine the properties of 3D printing and 4D printing, this part makes it to move in what way to respond to external stimuli. In case of 4D printing with SMP, it raises the temperature higher than the glass temperature for the material that has been produced by printing at the prior stage and makes strain to be applied through transformation of appearance. ^[8]

Actuation process

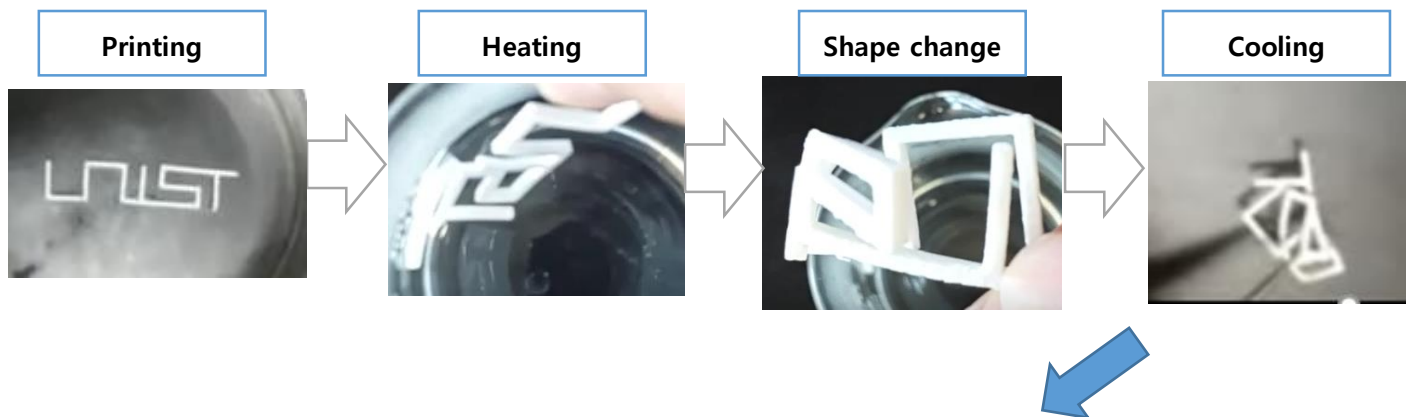
This is to actuate the stage that was programmed before through applying stimuli from outside. In the case of 4D printing using SMP, it's the stage that the appearance returns to the original shape when the strain applied inside the material by transformation of appearance at the foresaid stage is released at a higher temperature than the glass temperature.

We performed this 4D printing test with SMP as well through the stages of printing, programming, and actuating. When performing the test, we used PLA and conductive PLA for SMP materials, and for 3D printer, we used Replicator (5th generation) and Replicator2X of MakerBot. In the case of the PLA we used, its glass temperature is 60~65 degrees Celsius and the melting temperature is 150~160 degrees Celsius. When printing, we used 215 degrees Celsius for the temperature of nozzle. In the case of conductive PLA, it was 215 degrees Celsius for the temperature of nozzle. ^{[2][5][19]}

The printing process (3D printing)



The programing process (4D printing)



The actuator process (4D printing)

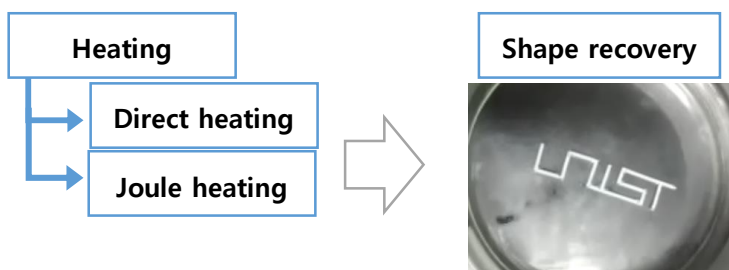


Figure 3-2.1

The 4D printing process

The 4D printing process using SMP generally is composed of printing, programing and actuator.

3-3. test samples

We performed, in total, 4 experiments for the basic 4D printing test using SMP. In all tests, we programmed and actuated with around 85 degrees Celsius water.

Unist word

Unist word is the experiment that we performed the very first in order to see the shape memory capability of SMP, and after making the letters of UNIST and we could confirm the original properties of SMP through the test that returned to the original shape.

Lattice expansion

The experiment of lattice expansion was a test in which we made several lattices and restored them into their original size again after having compressed them. From the results at this time, we could verify the possibility that can change the size of various structures through 4D printing using SMP.

Swelling into 3D structure

The last experiment using PLA was to show the possibility that the shape of 2D can transform into that of 3D. Through this experiment, we can confirm that the plane of 2D changes into the cylinder shape of 3D form.

Drone wing recovery

Lastly, we performed a test with conductive PLA which was mixed with graphite. We confirmed that we can actuate through electricity when we use conductive PLA. We produced a structure assuming a drone wing. We could confirm the possibility that we have the drone wings fold and unfold together with the operation by electricity. It took around 15 seconds for the first photo to change into the final photo (Figure 3-3.4). We confirmed through a COMSOL simulation in order to check the distribution that the current of conductive PLA before testing flows and how long distance it must flow to the maximum if we can raise the temperature higher than the glass temperature. Since we wanted to have the difference of process as a variable in simulation, we made the distances that the current flows

different using a ladder shape that has various process of distance. For the simulation conditions in COMSOL, we used the interpretation of electric currents and made the applied voltage flow from the lower right to the upper right, and the input voltage was 30V. We used the estimated value of $6 \times 10^{-4} \text{ S/m}$ for the electrical conductivity of the material.



Figure 3-3.1

Word (UNIST)

Top: initial state

Bottom: final state

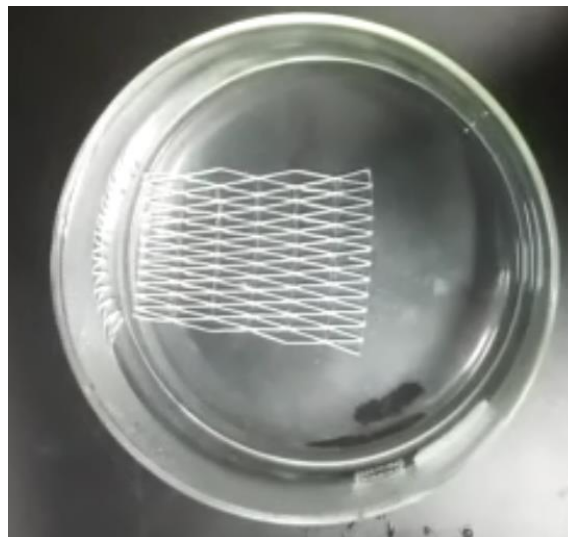


Figure 3-3.2

Lattice expansion

Top: initial state (contraction)

Bottom: final state (expansion)



Figure 3-3.3

Swelling into 3D structure

Top: initial state (2D structure)

Bottom: final state (cylinder)



Figure 3-3.4

Drone wing recovery

Top: initial state (folded drone wing)

Bottom: final state (unfolded drone wing)

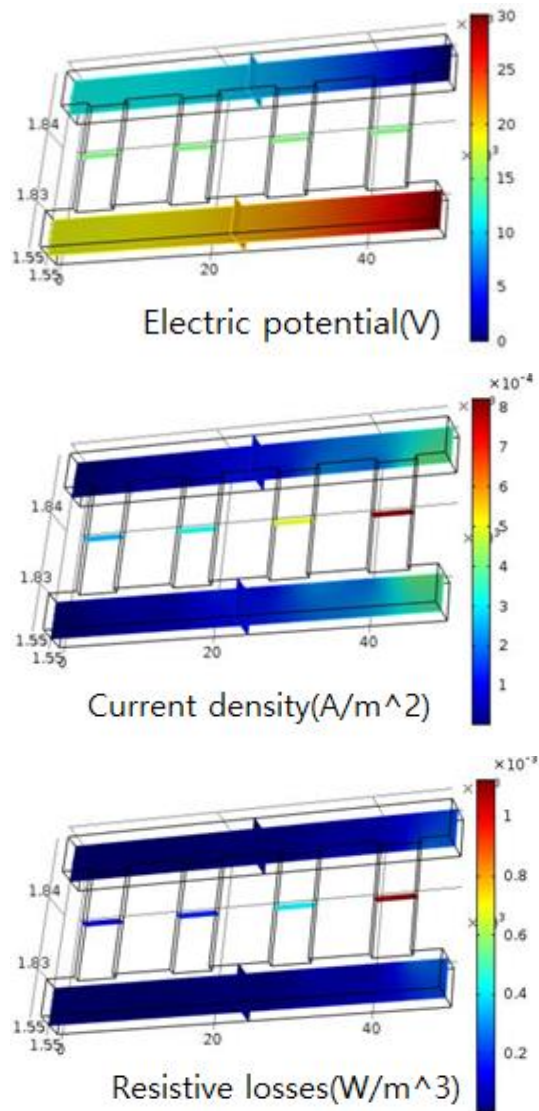


Figure 3-3.5

Distributions of electric potential, current density, resistive losses in Conductive PLA

30V has been applied at the lower right source, and the upper right side is the drain part and 0V has been applied there.

3-4. Method to overcome SMP disadvantages

Through the 4 tests that we showed earlier, we confirmed that many diversified functions can be assigned with 4D printing. In addition to the method of direct heating to raise temperature, we could also find that we can actuate through heating by electricity after mixing graphite to PLA. However, we also found from the results that it still has a relatively slow response speed and disadvantages like the relatively weak force of PLA. In order to solve these problems, we performed additional experiments using elastic energy to overcome the disadvantages.

Idea to solve disadvantages

The biggest disadvantage that we can see when using the shape memory ability of SMP matter as it is, is that the response occurs slowly and the force that the material has is very small. So, we thought that a different force except the ability of SMP of SMP matter itself is needed to overcome this and thus we made a different elastic energy be able to give help. As a result, we came to be able to produce the programmable matter that efficiently responds in a shorter time with stronger force using both the elastic energy and the strain stored in SMP together. For the method of use, we store the elastic energy of material and have the elastic energy stored in SMP matter be maintained. After that, when adding stimuli from outside, the response of SMP makes the stored elastic energy possible to be released and it responds. In other words, it's a method that SMP plays the role of a trigger and we actually get and use the force from the elastic energy. For an idea test, we made a catapult using ABS and conductive PLA. The structure of catapult is composed of a part storing the elastic energy and a part of trigger. Part A in the picture (Figure 3-4.1) is the part storing the elastic energy and part B is the part that is made of conductive PLA and plays the role of trigger. For the heating method to actuate the catapult, we used direct heating and Joule heating. For direct heating, we actuated by a heat gun. In case of Joule heating, we applied around 0.04~0.06A to 30V and actuated.

Manufacture process

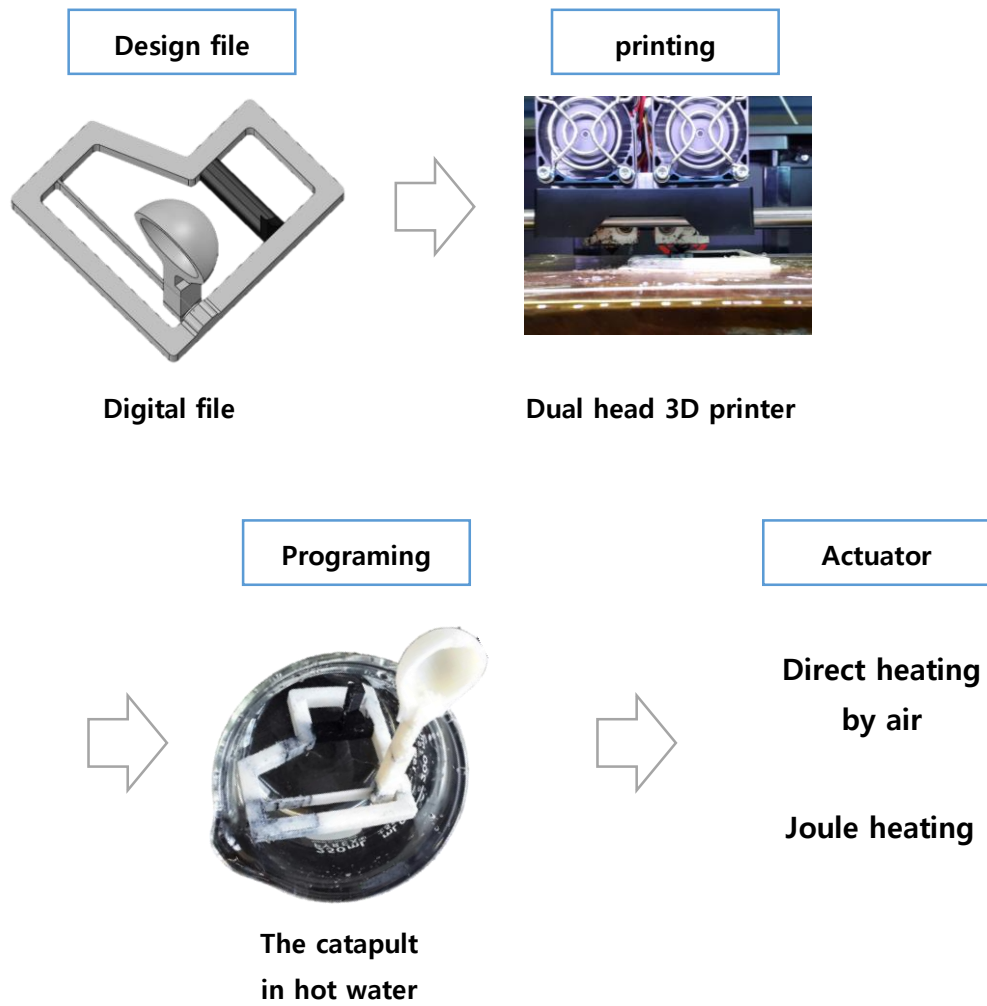


Figure 3-4.1

Catapult manufacture process

It has the same process as the 4D printing using SMP explained earlier.

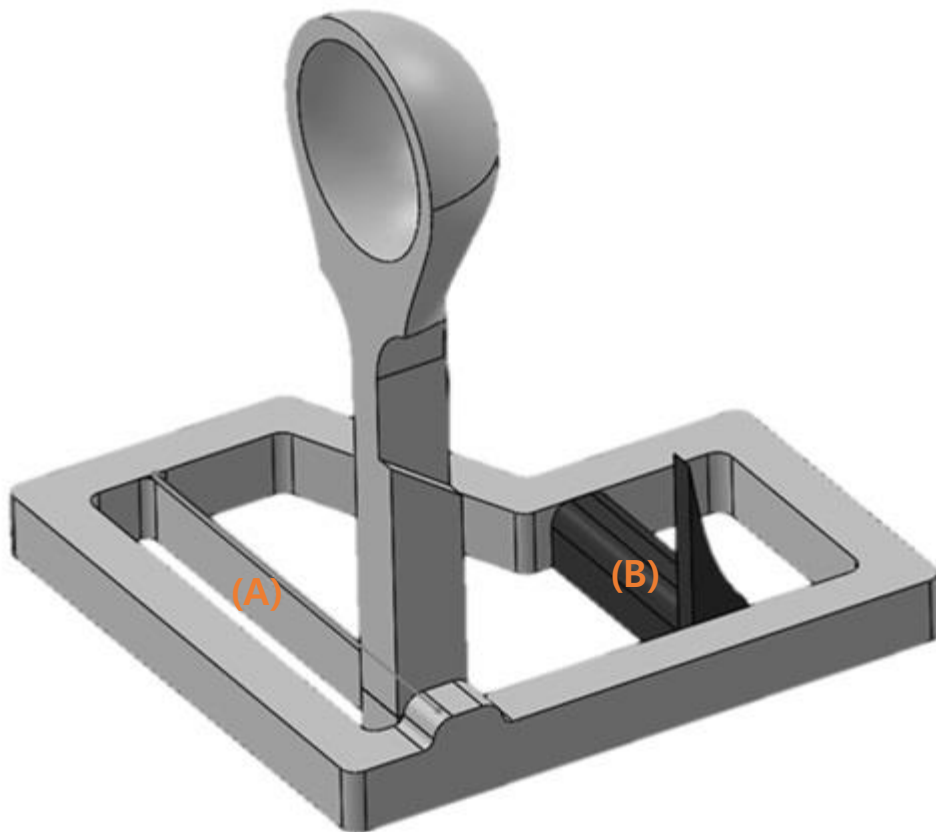


Figure 3-4.1

Catapult structure

Part (A) is the part storing the elastic energy and the black part (B) is the part playing the role of trigger.

Hot
wind

Over 100 °C

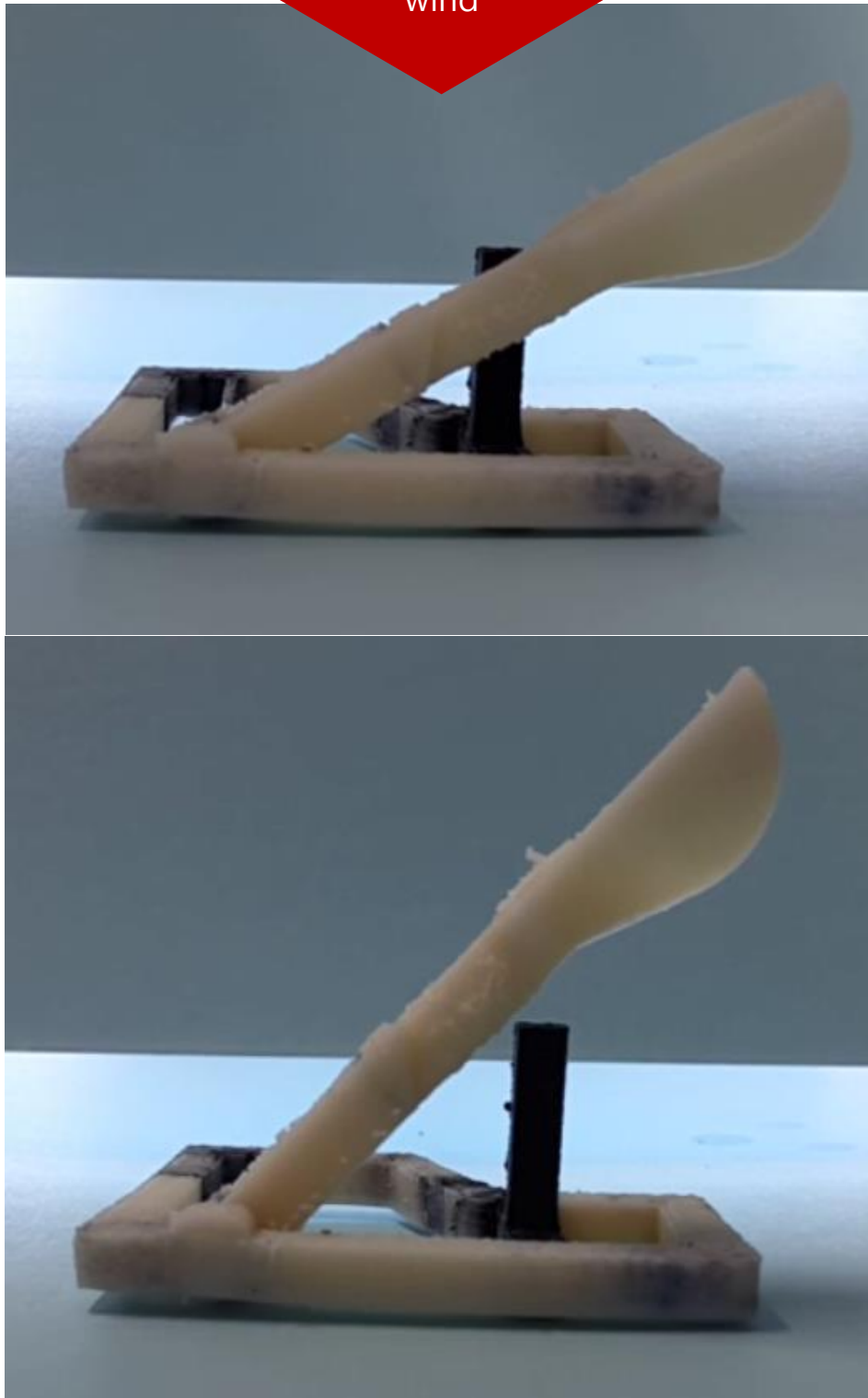


Figure 3-4.2

Catapult responded by heat gun

The catapult that operates responding to the direct heating that uses a heat gun.

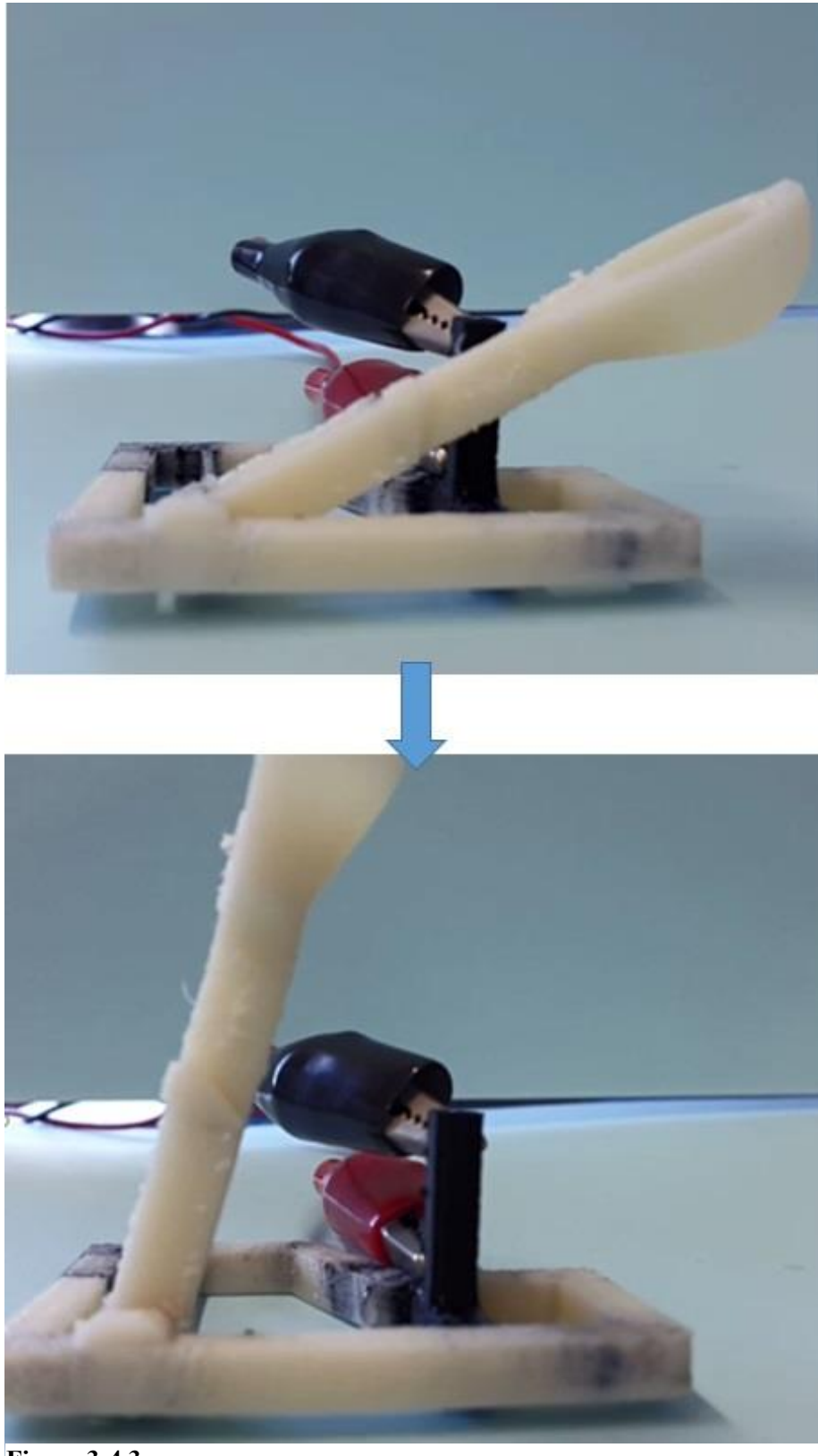


Figure 3-4.3

Catapult responded by Joule flow

The catapult operating in response to Joule heating.

Applied voltage: 30V (Current: 0.04~0.06A)

4. Mechanical Bistable structure

In this study, we performed an experiment using a bistable structure to make the programmable matter that responds to external forces. The bistable structure is a structure that has two stable states. We can commonly find this structure in our surroundings like smartphone cradles and also find the examples like Venus flytrap^[21] in the natural world. For this experiment, we made a mechanical bistable structure that responds linearly^[22], rotationally^[23], and twistedly to the external forces. These three sets belong to the basic components that make complicated movements. In other words, we came to be able to realize various complicated movements from the mechanical bistable structure we made this time. Additionally, we expect that we can make more efficient devices as well if we adapt it to 4D printing using SMP, as was performed earlier.

4-1. Background of bistable structure

The bistable structure has two states in which it can be stable. If drawing an energy diagram to help understanding, it would be the picture (Figure 4-1.1) below.^[24] If looking at the picture, we can find that there are two stable states on both sides which are state A and state B with an energy barrier between them. The property of bistable objects is that they move automatically to the other state when receiving a force bigger than the energy barrier. If using this, we can make the programmable matter through 3D printing, which operates responding to the external forces.^[22-23]

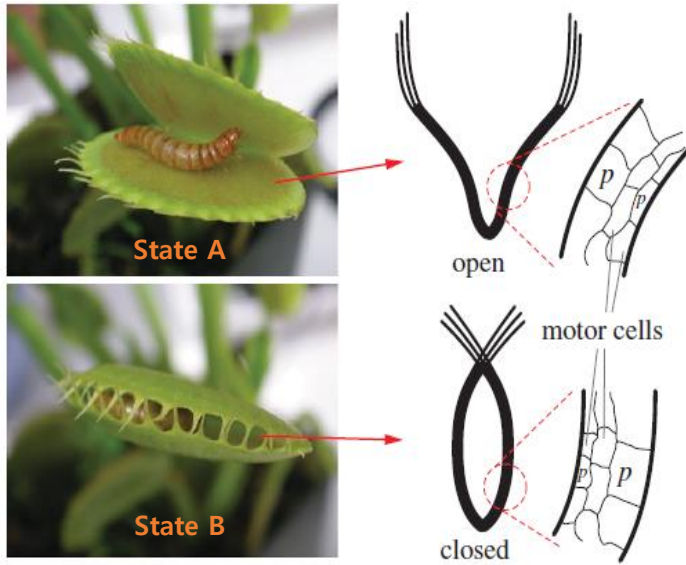


Figure 4.1

Venus flytrap ^[21]

The plant is one example of bistable structure in nature.

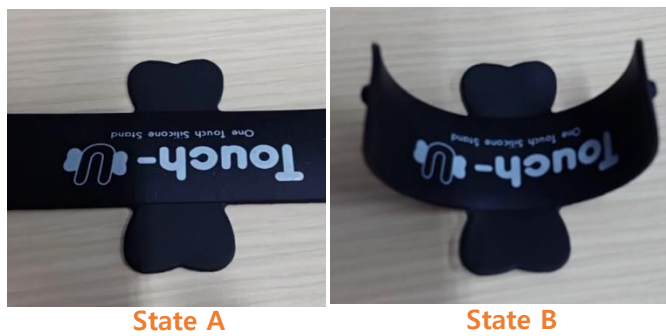


Figure 4.2

Smartphone cradle

Bistable structure example

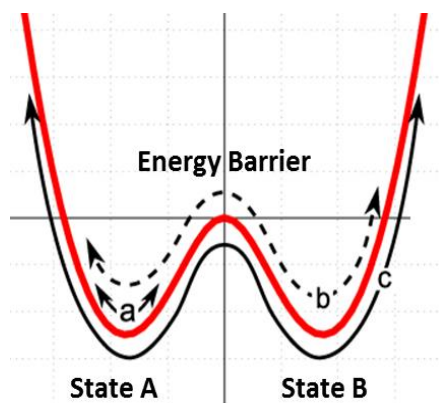


Figure 4-1.1

Energy diagram of Bistable structure ^[24]

The energy diagram has two stable state

4-2. Bistable basic elements

We made three structures capable of flipping, rotating, and twisting respectively for the bistable basic elements. Each element of the three kinds is the most fundamental element for various complicated movements. If combining these well, we can realize complicated movements like human arms. We used J750 model (3D printer) of Stratasys and the digital ABS (materials) made by Stratasys. We have not yet correctly measured the force applied to the manufactured components, but it is estimated that the force necessary to cross over the energy barrier would be around 1N~5N.

The flipping bistable structure

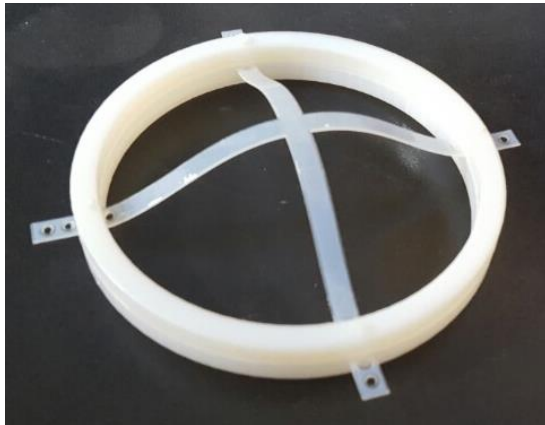
This is a structure in which the middle part moves up and down and makes linear movements. ^[22] For this structure, we manufactured two structures, i.e. asymmetric structure and symmetric structure. Since the asymmetric structure is useful when making a big effect with a small force and the symmetric structure is useful when coming and going between state A and B. We performed a simulation about the case of asymmetry using SOLIDWORKS, and we could confirm that it was below the maximum value the material (digital ABS) can bear since the maximum Von Mises stress that the material received was $5.132 \times 10^7 \text{ N/m}^2$. The symmetric structure has better durability than asymmetric structure, it was manufactured possible to be tuned. It has a disadvantage that we have to manually assemble in person after printing.

The rotational bistable structure

This is a structure that can rotate. ^[23] We also prepared the structures of asymmetry and symmetry for this structure. In case of asymmetric structure, we made it with a small rotation angle (about 15°) and it is useful when a big effect is needed with a small force. In the case of the symmetrical structure, it has higher angle (about 90°) of rotation and durability using the pin structures on both ends, and it is useful when crossing over between state A and B is needed. We performed a simulation about the symmetric structure using SOLIDWORKS. We can also verify that it is below the limit of material since its maximum Von Mises stress is $6.642 \times 10^7 \text{ N/m}^2$.

The twist bistable structure

This is similar to the rotational structure, but this structure is made twisted for the rotation to be moved to a different place. In order to produce this kind of structure, we manufactured one to be able to move in any direction since we judged that we had to give a degree of freedom higher than the pins at the connecting parts. For this structure, we manufactured only the symmetric structure. Performing a simulation using SOLIDWORKS, we could verify that the maximum Von Mises stress was $5.059 \times 10^7 \text{ N/m}^2$, which is below the limit of material.



State A



State B

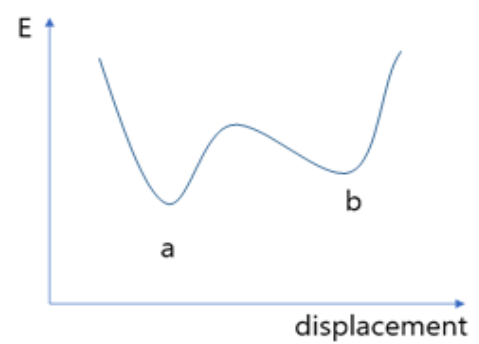
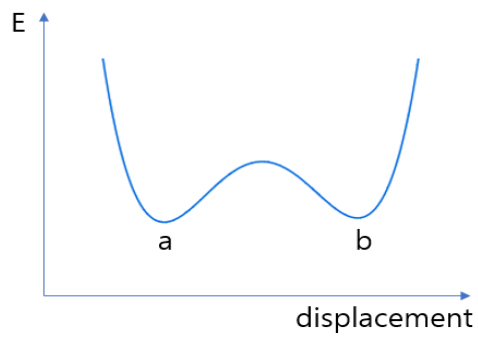


Figure 4-2.1

The flipping bistable structure

Right: symmetric structure

Left: asymmetric structure

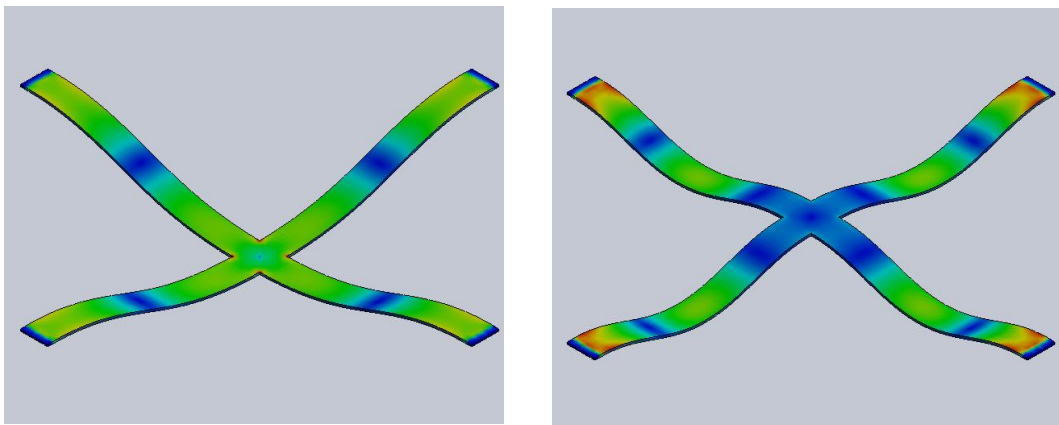


Figure 4-2.2

The simulation result of the asymmetric flipping bistable structure

Right: final structure state Left: state when Von Mises stress is maximum

Color indicates the degree of Von Mises stress.

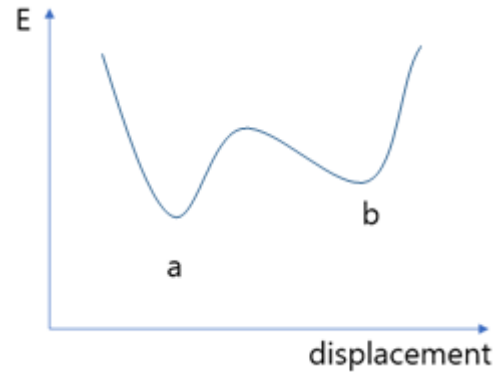
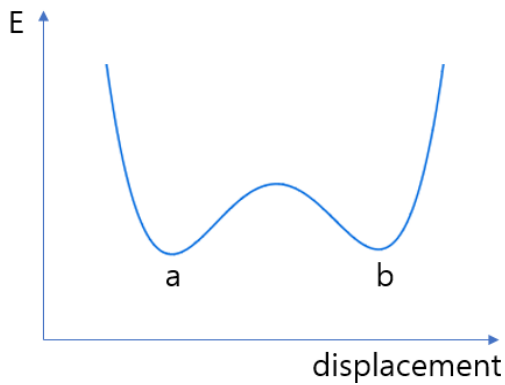
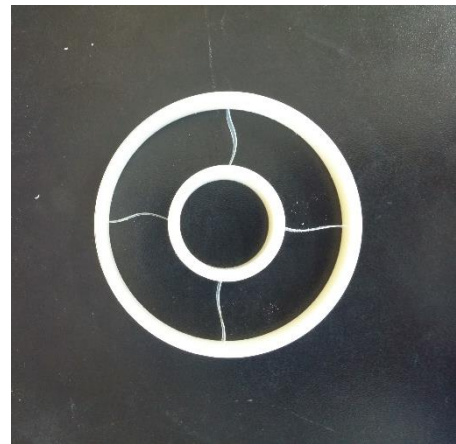
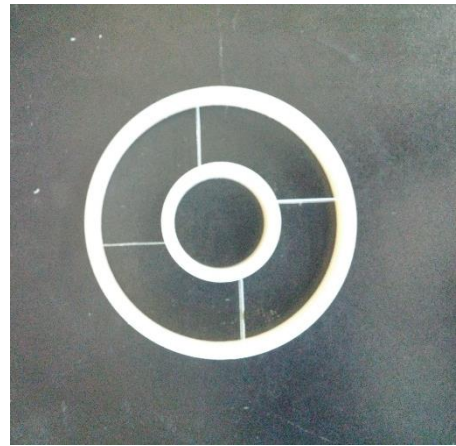


Figure 4-2.3

The rotational bistable structure

Right: the symmetric rotational bistable structure, the structure has a rotation angle of 90degrees with pin connectors.

Left: the asymmetric rotational bistable structure, the structure has a rotation angle of 15degrees.

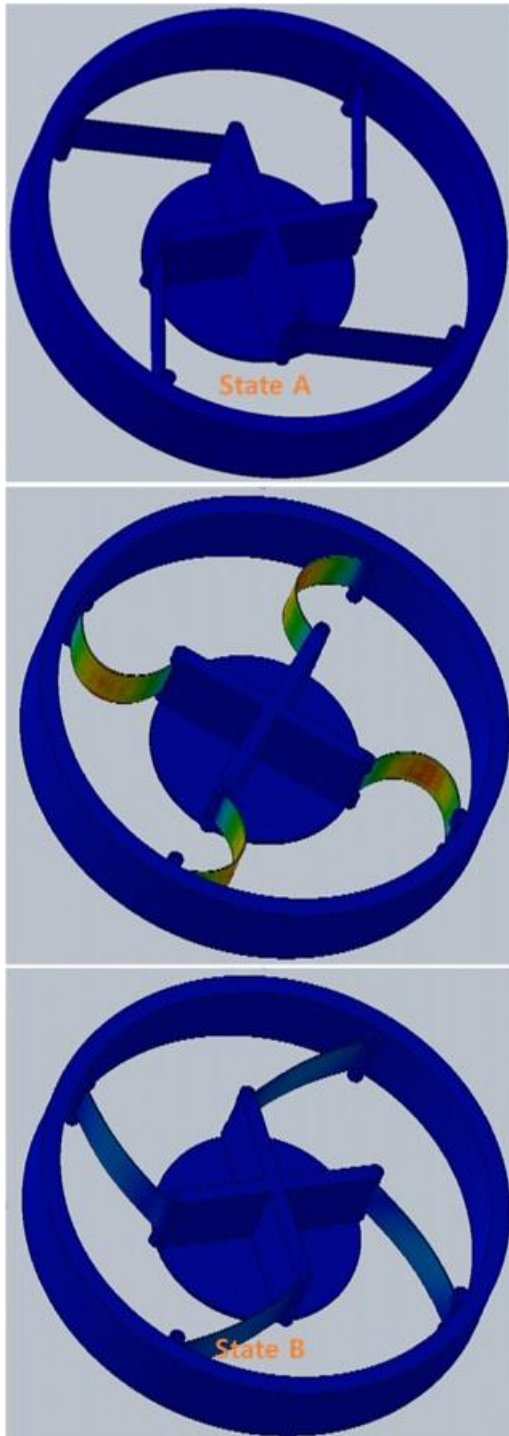


Figure 4-2.4

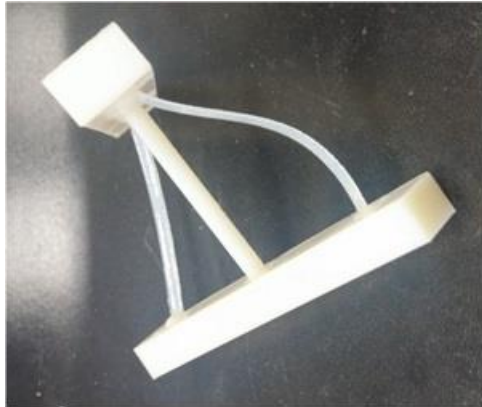
The simulation result of the asymmetric flipping bistable structure

Top: initial structure state.

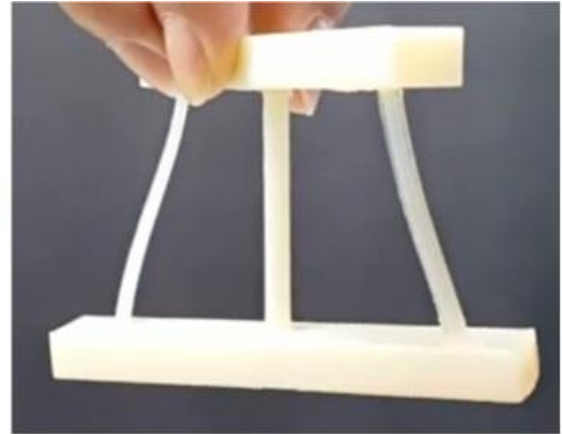
Middle: state when Von Mises stress is maximum.

Bottom: final state.

Color indicates the degree of Von Mises stress.



State A



State B

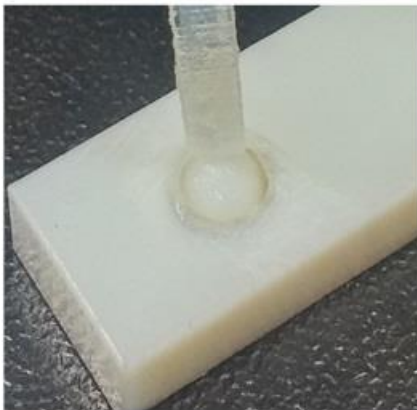
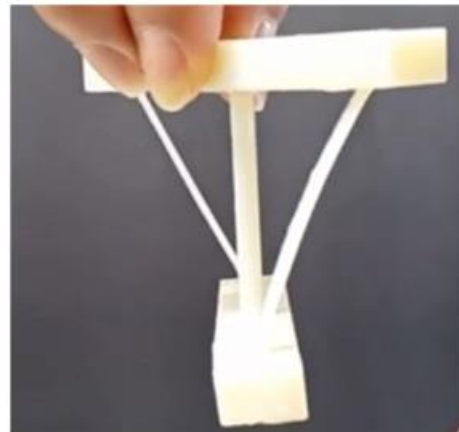


Figure 4-2.5

The twist bistable structure

The connector has a high degree of freedom than pin connector because it has a spherical shape.

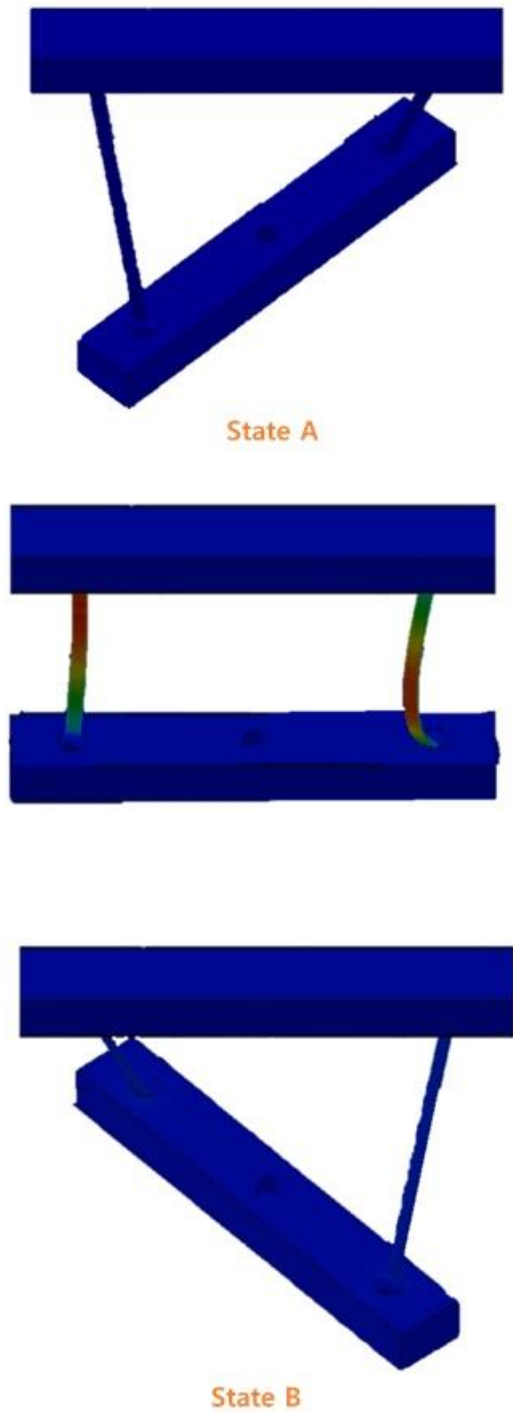


Figure 4-2.6

The simulation result of the asymmetric flipping bistable structure

Top: initial structure state.

Middle: state when Von Mises stress is maximum.

Bottom: final state.

Color indicates the degree of Von Mises stress.

5. Summary

In this study, we performed a research to find the direction that 4D printing will be developed in the future and to check what things are possible to happen. Through the experiment performed first, we checked that what shape of programmable matter we can produce with 4D printing using SMP. When using SMP, we could verify that transformation of various shape is possible such as expansion of material, and confirm the possibility to apply this to other diverse fields. However, we also found that there are limitations such as slow speed of response and weak force. In order to solve the disadvantages of SMP matter like this, we produced a structure that operates by different forces like the elastic force and SMP plays only the role of trigger.

As an example, we produced a catapult with this method in this study. Lastly, we manufactured a mechanical bistable structure. The mechanical bistable structure is a programmable matter that responds to external forces. Beginning with the flipping bistable structure that exercises linear motions, we made the rotational structure and twist structure in this study. It is expected that if harmonizing these three kinds of structures each other, we can realize more complicated movements. In addition, if combining it with the SMP mentioned earlier, we can secure more possibilities to apply. To speak the meaning of this study lastly, we performed a basic study to progress the 4D printing that is combined with SMP and bistable structure.

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